



# Paleoceanography

## RESEARCH ARTICLE

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### Key Points:

- Subduction depth of AAIW-depth varies on glacial/interglacial timescales
- Shoaling of AAIW leads to an expansion of UCDW
- UCDW shoaling enlarges the glacial carbon pool

### Supporting Information:

- Text S1 and Tables S1–S2
- Figure S1
- Figure S2

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## Pushing the boundaries: Glacial/interglacial variability of intermediate and deep waters in the southwest Pacific over the last 350,000 years

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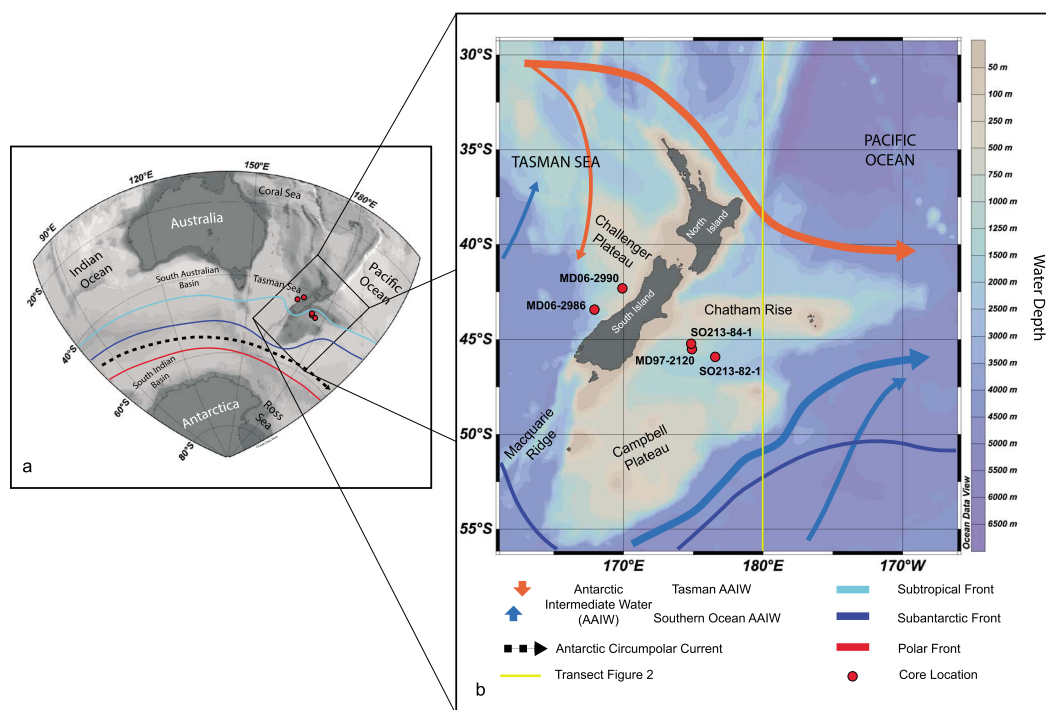
**Abstract** Glacial/interglacial changes in Southern Ocean's air-sea gas exchange have been considered as important mechanisms contributing to the glacial/interglacial variability in atmospheric CO<sub>2</sub>. Hence, understanding past variability in Southern Ocean intermediate to deep water chemistry and circulation is fundamental to constrain the role of these processes on modulating glacial/interglacial changes in the global carbon cycle. Our study focused on the glacial/interglacial variability in the vertical extent of southwest Pacific Antarctic Intermediate Water (AAIW). We compared carbon and oxygen isotope records from epibenthic foraminifera of sediment cores bathed in modern AAIW and Upper Circumpolar Deep Water (UCDW; 943–2066 m water depth) to monitor changes in water mass circulation spanning the past 350,000 years. We propose that pronounced freshwater input by melting sea ice into the glacial AAIW significantly hampered the downward expansion of southwest Pacific AAIW, consistent with climate model results for the Last Glacial Maximum. This process led to a pronounced upward displacement of the AAIW-UCDW interface during colder climate conditions and therefore to an expansion of the glacial carbon pool.

## 1. Introduction

Surrounding Antarctica, the Southern Ocean (SO) plays a vital role in the global overturning circulation as it connects the Pacific, Atlantic, and Indian Oceans. The transport of Antarctic Intermediate Water (AAIW) in particular is crucial for the redistribution of nutrients, heat, and freshwater within the global ocean [Schmitz, 1995; Toggweiler *et al.*, 1991]. On glacial/interglacial timescales, climate signals of upwelled deep water were transported from the Southern Ocean toward the major ocean basins within the AAIW [Basak *et al.*, 2010; Bryan *et al.*, 2010; Marchitto *et al.*, 2007; Stott *et al.*, 2009] and, at least during the last deglacial, AAIW was an important indicator for the transport of CO<sub>2</sub> from old deep water masses to the atmosphere [e.g., Marchitto *et al.*, 2007; Rose *et al.*, 2010]. Today, most of the anthropogenic CO<sub>2</sub> entering the ocean depths is contained within AAIW [Downes *et al.*, 2010; Murata *et al.*, 2007, 2010; Sabine *et al.*, 2004]. The importance of the oceanic uptake of CO<sub>2</sub> (not only via AAIW) becomes evident by the fact that without this process, the atmospheric CO<sub>2</sub> concentration would be about 55 ppm higher than it is today (~400 ppm) [Sabine *et al.*, 2004]. Despite the importance of AAIW for the global climate, especially in view of the current climate change, only scarce information about the temporal changes in its vertical and lateral expansion exists. In this study, we present new epibenthic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  records from the Chatham Rise and the Tasman Sea off New Zealand that span the last 350 kyr. In comparison to a previously published record from sediment core MD97-2120 (1210 m; 45°32'S 174°55'E) [Pahnke and Zahn, 2005] we are able to constrain the vertical extent of AAIW over different climatic cycles by using isotope records from multiple sediment cores from different water depths.

### 1.1. Regional Oceanography

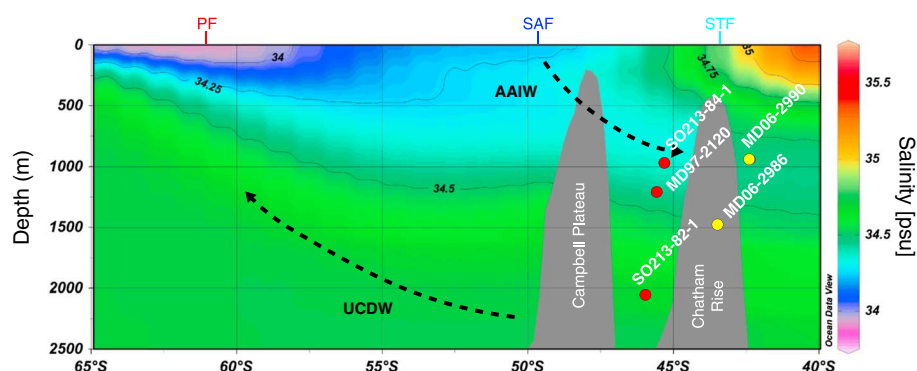
Dominating the SO, the Antarctic Circumpolar Current (ACC) is propelled by strong Southern Hemisphere Westerly Winds (SWW) [Rintoul *et al.*, 2001]. In our research area, the New Zealand microcontinent is significantly affecting the position of the ACC's northern boundary, the Subantarctic Front (SAF) [Carter and Wilkin, 1999]. South of New Zealand the Macquarie Ridge and the Campbell Plateau (Figure 1) dictate the location of the SAF [Heath, 1981]. Likewise, the northern edge of the SO, namely, the Subtropical Front (STF) is



**Figure 1.** Bathymetric and oceanographic map of the study area showing the major oceanic fronts and current systems in the Southern Ocean. (a) Supraregional overview map of the SW Pacific and Indian sector of the Southern Ocean. (b) Regional setting of the New Zealand subcontinent [After Orsi *et al.*, 1995; Bostock *et al.*, 2013a; Bostock *et al.*, 2013b].

forced to follow the continental shelf of the submerged microcontinent and is topographically restricted by the submerged Chatham Rise (Figure 1b) [Crundwell *et al.*, 2008; Heath, 1981; Sutton, 2003].

The subsurface southwest Pacific is subdivided into four major water masses. Subantarctic Mode Water (~300–800 m) [Crundwell *et al.*, 2008] is characterized by its uniform temperature (8–9°C) and high oxygen concentrations. In winter, Subantarctic Mode Water is formed via the process of deep mixing along the SAF [Bostock *et al.*, 2013a; McCartney, 1977]. Further down, Antarctic Intermediate Water (AAIW) expands the prominent salinity minimum into a depth between 800 and 1450 m (Figure 2) [Hayward *et al.*, 2002; Heath, 1985; McCartney, 1977; Sloyan *et al.*, 2010]. South of the Chatham Rise, in our research area, intermediate waters originate directly from the ACC [Hayward *et al.*, 2002]. Intermediate waters to the north of the Chatham Rise are modified by the admixture of waters from the Coral and Tasman Seas [Bostock *et al.*, 2013a; Tomczak and Godfrey, 1994]. Bostock *et al.* [2013b] refer to the intermediate waters, formed in a small region close to the SAF off New Zealand as Southern Ocean AAIW. This SO AAIW forms directly from upwelled nutrient- and CO<sub>2</sub>-rich Circumpolar Deep Water (CDW). Accordingly, the chemical signature of AAIW carries information about the efficiency of the biological pump and air-sea gas exchange [Sigman *et al.*, 2010]. Simplified, the remaining nutrient concentration of sinking AAIW is a measure of the difference of upwelled nutrients and biological consumption in the uppermost water column, while the overturning intensity is modified by the strength of the wind-induced upwelling. The associated processes within this loop from upwelling to sinking are crucial for the oceanic release or uptake of atmospheric CO<sub>2</sub>. Below the AAIW, CDW as the most voluminous SO water mass [Carter *et al.*, 2009] is subdivided into two distinctive water masses. Upper CDW (UCDW; ~1450–2900 m) outcrops around Antarctica and is defined by an oxygen minimum that is formed by the influence of old deep waters from the North Pacific and Indian Oceans [Callahan, 1972; Carter *et al.*, 2009]. Increased salinity by the entrainment of North Atlantic Deep Water marks the Lower CDW (LCDW; ~2900–4500 m) [Callahan, 1972; Orsi *et al.*, 1995]. Below ~3900 m, LCDW is influenced by cold Antarctic Bottom Waters [Bostock *et al.*, 2013a]. According to McCave and Carter [1997], the majority of deep water (>2000 m) entering the Pacific Ocean is transported via a strong deep western boundary current (DWBC) southeast of New Zealand. Moving a volume of about 20 Sv, the Pacific DWBC is one of the strongest boundary currents worldwide [Schmitz, 1995].



**Figure 2.** Salinity section along the 180° meridian (indicated in Figure 1b; WOA; [Antonov *et al.*, 2010]). To project the analyzed sediment cores (red dots = Bounty Trough and yellow dots = Tasman Sea) in this section, their longitudes were adjusted to 180°. Arrows indicate the prevailing current regime of SW Pacific water masses. AAIW = Antarctic Intermediate Water, UCDW = Upper Circumpolar Deep Water, PF = Polar Front, SAF = Subantarctic Front, and STF = Subtropical Front.

## 2. Material and Methods

We analyzed four sediment cores from the Tasman Sea and the Bounty Trough off New Zealand, collected during R/V *Marion Dufresne* MD152 and R/V *Sonne* SO213/2 cruises in 2006 and 2011, respectively [Proust *et al.*, 2006; Tiedemann, 2012]. Cores MD06-2990 (943 m; 42°19'S 169°55'E) and MD06-2986 (1477 m; 43°27'S 167°54'E) were collected in the Tasman Sea west of New Zealand. Cores SO213-84-1 (972 m; 45°07'S 174°34'E) and SO213-82-1 (2066 m; 45°46'S 176°36'E) are located on the eastern side of the island, in the Bounty Trough south of the Chatham Rise. Today, SO213-84-1 and MD06-2990 are bathed by AAIW, MD06-2986, and SO213-82-1 by Upper Circumpolar Deep Water (UCDW). The uppermost part of MD06-2990 was significantly disturbed during core recovery. We therefore used the top section of R/V *Sonne* core SO136-003 (42°17.74'S/169°52.66'E; 958 m water depth) [Thiede, 1999] to replace the affected sediment sequence (see description of the age model for additional information). Sediment core SO213-82-1 yields an average sedimentation rate of 3 cm/kyr, SO213-84-1 shows a sedimentation rate of 6 cm/kyr while MD06-2986 and MD06-2990 yield sedimentation rates of 8 cm/kyr and 3 cm/kyr, respectively. The working halves of both SO213 cores were sampled at 2 cm intervals. The top 13.50 m of core MD06-2990 (33.55 m length) and the top 2.50 m of core SO136-003 were sampled at 2 cm intervals, core MD06-2986 (32.68 m length) was sampled at 4 cm intervals. Subsequently, the samples were frozen and freeze dried for 2 to 3 days, depending on the samples' water content. After freeze drying, the samples were wet sieved through a sieve with a mesh size of 63  $\mu$ m and dried for two days at ~50°C. When dry, the samples were fractionated through different mesh sieves (125  $\mu$ m, 250  $\mu$ m, 315  $\mu$ m, and 400  $\mu$ m). The foraminifera were picked from the size fractions 250–315  $\mu$ m and 315–400  $\mu$ m using a reflective light microscope with a fiftyfold magnification.

### 2.1. Stable Isotopes

Isotope ratios (reported in delta notation versus VPDB calibrated via international standard NBS19) of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  were measured on four specimens of *Cibicides wuellerstorfi* or on three specimens of *Uvigerina peregrina*, in samples lacking a sufficient amount of *C. wuellerstorfi*. All measurements were conducted at the Alfred Wegener Institute in Bremerhaven, using a Finnigan MAT 253 mass spectrometer with a Kiel IV Carbonate Device. The long-term precision based on an internal laboratory standard (Solnhofen limestone) measured over a 1 year period together with samples was better than  $\pm 0.06\text{‰}$  for  $\delta^{13}\text{C}$  and  $\pm 0.08\text{‰}$  for  $\delta^{18}\text{O}$ .

*C. wuellerstorfi* was present throughout all sediment cores. However, in a few intervals we used *U. peregrina*, where *C. wuellerstorfi* was absent (Figure S1 in the supporting information).

#### 2.1.1. Oxygen Isotopes

Primarily, we used the benthic  $\delta^{18}\text{O}$  signal for the development of our age models. In addition to changes in global ice volume [Shackleton, 1977], which provide the stratigraphic basis in our study, the benthic  $\delta^{18}\text{O}$  signal reflects variations in local temperature and/or salinity [Emiliani, 1955; Epstein and Mayeda, 1953]. In general, the  $\delta^{18}\text{O}$  values recorded by *C. wuellerstorfi* deviate by ~0.64‰ from *U. peregrina* values [Shackleton and Opdyke, 1973].

The  $\delta^{18}\text{O}_{\text{Cib} \& \text{Uvi}}$  values in the records of SO213-84-1 and SO213-82-1 show a very high correlation with a mean offset *C. wuellerstorfi*-*U. peregrina* of 0.48‰. Therefore, we used this offset of 0.48‰ to correct the Bounty Trough  $\delta^{18}\text{O}$  values of *C. wuellerstorfi* for species-specific fractionation [McCave *et al.*, 2008; Pahnke and Zahn, 2005] instead of using an offset of 0.64‰ [Duplessy *et al.*, 1988; Shackleton and Opdyke, 1973]. However, the Tasman Sea records MD09-2986 and MD06-2990/SO136-003 show a good correlation with an offset of 0.64‰ and were therefore rendered to Uvi-equivalent by adding 0.64‰, according to the accepted method [Shackleton and Opdyke, 1973].

### 2.1.2. Carbon Isotopes

In paleoceanography, the epibenthic  $\delta^{13}\text{C}$  records of the foraminifer *C. wuellerstorfi* are commonly used as a proxy for changes in water mass nutrient concentrations [Kroopnick, 1985; Zahn *et al.*, 1991]. The  $\delta^{13}\text{C}$  values in the water column strongly depend on the remineralization of  $^{12}\text{C}$ -enriched organic matter, which leads to the consumption of oxygen and the release of nutrients. Low  $\delta^{13}\text{C}$  values are therefore indicative of high-nutrient concentrations and weakly ventilated water masses. Furthermore, oceanic  $\delta^{13}\text{C}$  values are influenced by the release of terrestrial carbon during glacial times [Peterson *et al.*, 2014] as well as by thermodynamic [Broecker and Maier-Reimer, 1992] and biological effects [Farquhar *et al.*, 1989].

As described above, we used *U. peregrina* to fill the intervals barren of *C. wuellerstorfi*. Following the methods of Pahnke and Zahn [2005] and McCave *et al.* [2008], we disregarded the usual +0.9‰ *U. peregrina* to *C. wuellerstorfi* offset. As these authors showed, the epifaunal to infaunal  $\delta^{13}\text{C}$  difference off New Zealand is far from constant but varies on glacial to interglacial timescales as a function of  $\delta^{18}\text{O}_{\text{Uvi}}$ . Over the whole record, the average offset  $\Delta\delta^{13}\text{C}_{\text{Cib-Uvi}}$  is 0.81‰ and therefore close to the offset of 0.9‰. However, the addition of 0.9‰ proves to be impractical for the conversion of  $\delta^{13}\text{C}_{\text{Uvi}}$  in SO213-82-1, if just the epifaunal to infaunal offsets of the Holocene and the Last Glacial Maximum (LGM) are compared. During the Holocene, the mean  $\Delta\delta^{13}\text{C}_{\text{Cib-Uvi}}$  of SO213-82-1 is as high as 1.09‰ while the LGM offset is only 0.47‰. To account for this variable offset, we used the regression equation of McCave *et al.* [2008]:

$$\Delta\delta^{13}\text{C}_{\text{Cib-Uvi}} = 0.464\delta^{18}\text{O}_{\text{Uvi}} - 2.753 \quad (r = 0.629; n = 57)$$

A comparison of raw isotopic data to the corrected values of SO213-82-1 is shown in Figure S1.

### 2.2. Paleoпродукivity Calculations

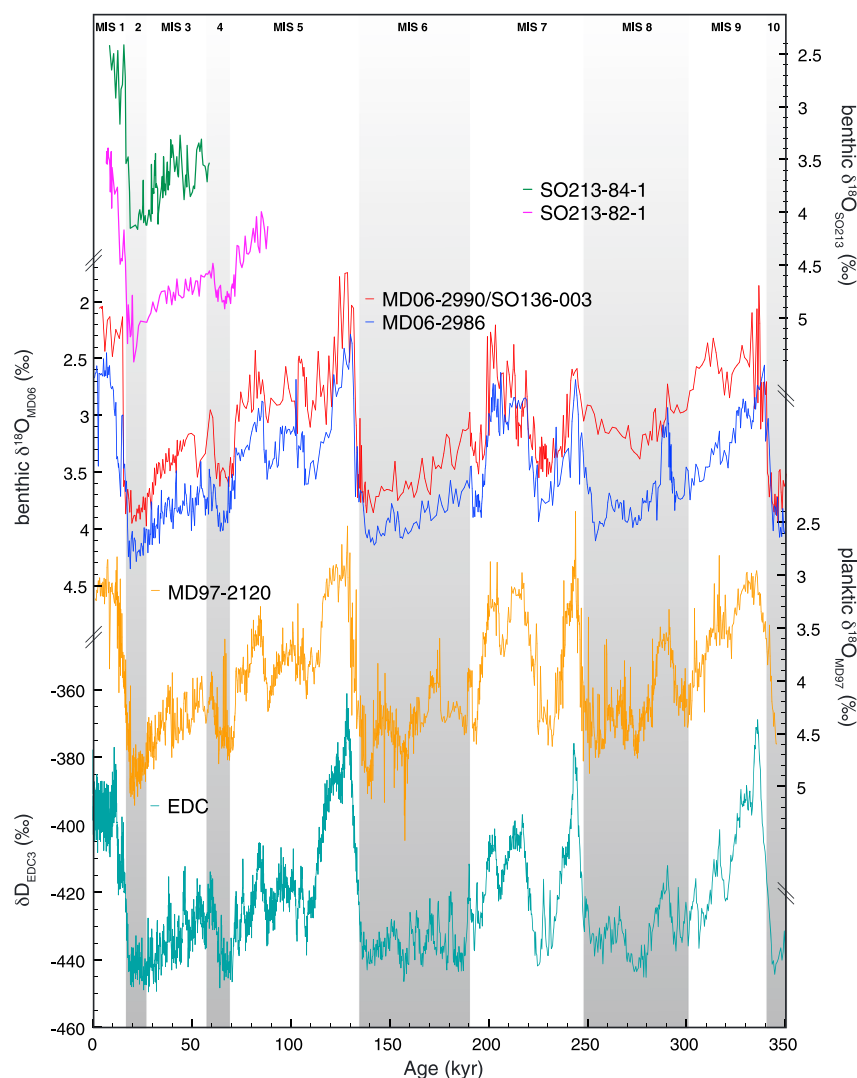
In order to assess the influence of phytodetritus (high in  $^{12}\text{C}$ ) on the benthic  $\delta^{13}\text{C}$  signals [Mackensen *et al.*, 2001], we calculated the paleoproduckivity for sediment cores SO213-82-1 and SO213-84-1 (Bounty Trough). Physical properties were measured with a spacing of 10 cm, using a PC controlled Eltra CS-2000 Carbon Sulfur element analyzer. We reconstructed the paleoproduckivity (PP; gC/m<sup>2</sup>/yr) according to Stein [1991]:

$$\text{PP} = 5.31 \left( \text{C}_{\text{org}}(\text{DBD}) \right)^{0.71} \times \text{LSR}^{0.07} \text{DEP}^{0.45}$$

DBD is the dry bulk density,  $\text{C}_{\text{org}}$  (%) is the content of organic carbon, LSR is the linear sedimentation rate (cm kyr<sup>-1</sup>), and DEP is the sediment cores water depth.

### 2.3. Age Determination

Our age models reflect a combination of radiocarbon dating and  $\delta^{18}\text{O}$  correlation to age scaled reference records. The age model for the upper section of cores MD06-2986 and MD06-2990/SO136-003, SO213-82-1, and SO213-84-1 is based on Accelerator Mass Spectrometry (AMS)  $^{14}\text{C}$  dates. AMS  $^{14}\text{C}$  dating was performed on mixed planktic foraminifera (MD06-2986, eight samples; Table S1), on *Globorotalia inflata* (SO136-003, six samples; Table S1) or on *Globigerina bulloides* (SO213-82-1, seven samples; SO213-84-1, three samples). The samples were prepared and analyzed in the Leibniz-Laboratory for Radiometric Dating and Isotope Research at the Christian-Albrechts-University of Kiel (MD06-2986), at the AMS  $^{14}\text{C}$  Laboratory at the Eidgenössische Technische Hochschule Zürich (SO136-003) and at the NOSAMS facility in Woods Hole, USA (SO213-82-1 and SO213-84-1). AMS  $^{14}\text{C}$  ages were converted to calendar ages using CALIB 7.0 of M. Stuiver *et al.* (2014, CALIB 7.0. WWW program and documentation), applying a local reservoir correction of 640 years for interglacial and 1970 years for glacial age [Pahnke and Zahn, 2005; Sikes *et al.*, 2000]. Beyond the range of radiocarbon dating, the age scale for our cores was obtained by correlating the oxygen isotope records (mainly indicative of changes in global ice volume) with the EPICA Dome C ice core (EDC)  $\delta\text{D}$  record on the AICC2012 timescale [Bazin *et al.*, 2013; Jouzel *et al.*, 2007; Veres *et al.*, 2013] (Figure 3). To guarantee the best possible correlation, we updated the MD97-2120 age model of Pahnke and Zahn [2005] to the EDC ice core



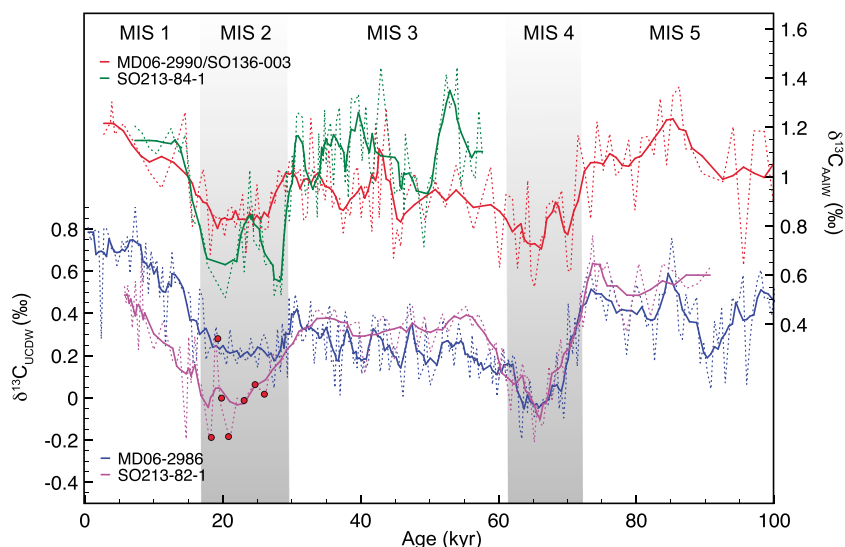
**Figure 3.** Benthic  $\delta^{18}\text{O}$  isotope records measured on *C. wuellerstorfi*. Bounty Trough sediment cores SO213-82-1 (pink) and SO213-84-1 (green); Tasman sea records MD06-2986 (blue) and MD06-2990 (red). Isotope record of MD97-2120 (orange; [Pahnke and Zahn, 2005]) was measured on the planktic species *G. bulloides*. EPICA dome C  $\delta\text{D}$ -curve on the AICC2012 timescale (teal) [Bazin et al., 2013; Jouzel et al., 2007; Veres et al., 2013]. Marine Isotope Stages: MIS 1 to MIS 10. Grey shadings indicate glacial stages.

and correlated our isotope records in the following to MD97-2120. Furthermore, we combined the benthic  $\delta^{18}\text{O}$  records for cores SO136-003 and MD06-2990. The uppermost part, comprising the interval of Marine Isotope Stage (MIS) 1 to MIS 4 (0–65 kyr), is based on SO136-003, while the record below, down to 350 kyr (MIS 4 to MIS 10) is based on MD06-2990. Tuning our benthic  $\delta^{18}\text{O}$  records to the EDC  $\delta\text{D}$  record resulted in a generally good agreement with the previously published benthic  $\delta^{18}\text{O}$  record of core MD97-2120, collected from 1200 m water depth on Chatham Rise east of New Zealand (Figure 3) [Pahnke and Zahn, 2005].

#### 2.4. Climate Modeling

In order to test hypothesized mechanisms that may have affected the characteristics and distribution of AAIW during glacial climates, we analyzed results from a glacial climate simulation using the Community Climate System Model version 3 (CCSM3). CCSM3 is a state-of-the-art fully coupled global general circulation model which is composed of four components representing the atmosphere, the ocean, the land surface, and sea ice [Collins et al., 2006]. For the simulation in this study, the atmosphere model has a resolution of  $\sim 3.75^\circ$  (T31 spectral truncation) with a vertical discretization of 26 levels, while the ocean and sea ice components are run on a nominal  $3^\circ$  grid with 25 levels in the ocean [Yeager et al., 2006].





**Figure 4.** Comparison of Bounty Trough (SO213) and Tasman Sea (MD06) AAIW and UCDW benthic  $\delta^{13}\text{C}$  (*C. wuellerstorfi*) records. Red dots indicate samples where *U. peregrina* was measured and transformed to *C. wuellerstorfi* equivalent according to McCave *et al.* [2008]. Throughout the whole time interval MD06-2986 (blue) and SO213-82-1 (pink) are bathed by UCDW, while MD06-2990/SO136-003 (red) and SO213-84-1 (green) are bathed by AAIW. Bold lines (five-point running average); stippled lines (raw data). Grey shadings as shown in Figure 3. The pronounced offset of SO213-82-1 and MD06-2986 during MIS 2 might derive from the use of *U. peregrina* in SO213-82-1 in this time interval.

Besides a preindustrial control run, a simulation of the LGM has been carried out [Merkel *et al.*, 2010]. This simulation takes into account the orbital parameters, the greenhouse gas concentrations, and the ice-sheet distribution of the LGM (21 kyr before present). Moreover, a sea level lowering of 120 m has been taken into account by a modification of the land-sea distribution, which for instance, leads to closure of the Bering Strait. For details of the experimental setup and spin-up procedure to obtain statistical equilibrium climates, the reader is referred to Merkel *et al.* [2010].

### 3. Results

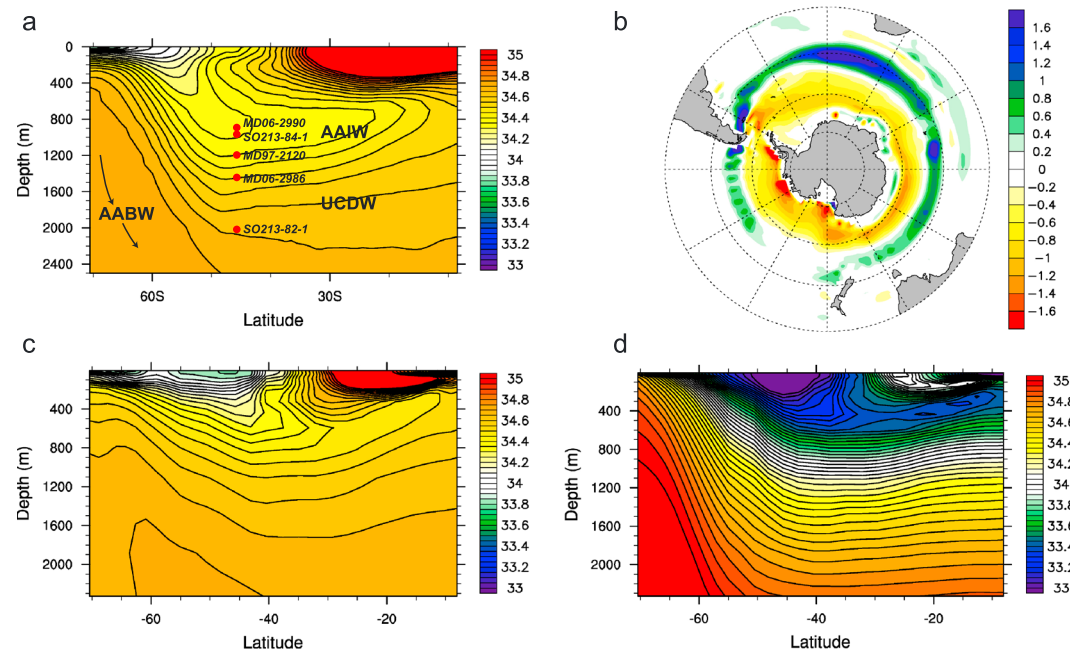
Here we present proxy records from the four sediment cores described in section 2, which are indicative of changes in intermediate and deep water circulation (benthic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) and biogenic productivity ( $\text{TOC}_{\text{AR}}$ ) in our study area. These records allow us to identify climate-driven variations in the vertical extent of AAIW and UCDW. The two Tasman Sea records MD06-2086 and MD06-2990 span at least the last four glacial/interglacial cycles from 0 to 350 kyr, while SO213-84-1 and SO213-82-1 from the Bounty Trough do not exceed the last 100 kyr.

The close correlation of the Bounty Trough and Tasman Sea isotopic records in both AAIW (Figure 4 (top)) and UCDW (Figure 4 (bottom)) enables us to compare the water masses on both sides of New Zealand (Figure 1b).

#### 3.1. Benthic $\delta^{18}\text{O}$

Except for SO213-82-1, where occasional samples of *U. peregrina* had to be analyzed to complement the record in depths barren of *C. wuellerstorfi* (see section 2), benthic  $\delta^{18}\text{O}$  records were measured on monospecific samples of *C. wuellerstorfi*.

All records display similar distinctive glacial-interglacial cycles. The variability of the epibenthic  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{Cw}}$ ) signal in our sediment cores reflects to a large part changes in global ice volume [Shackleton, 1977]. Yet the fact that the glacial/interglacial  $\delta^{18}\text{O}_{\text{Cw}}$  amplitudes of up to  $\sim 2\text{‰}$  in all cores generally exceed the sea level-related mean ocean  $\delta^{18}\text{O}$  change of 0.8 to  $1.1\text{‰}$  [e.g., Waelbroeck *et al.*, 2002] indicates that a relevant portion of the  $\delta^{18}\text{O}_{\text{Cw}}$  signal can be attributed to changes in water temperature and/or salinity [Emiliani, 1955; Epstein and Mayeda, 1953]. Although the glacial/interglacial  $\delta^{18}\text{O}_{\text{Cw}}$  amplitudes are very similar in our records,  $\delta^{18}\text{O}_{\text{Cw}}$  at the shallow cores MD06-2990/SO136-003 (945 m) and SO213-84-1 (972 m) was generally less than at the deeper core sites MD06-2986 (1477 m) and SO213-82-1 (2066 m) during the last four glacial/interglacial cycles (average AAIW/UCDW  $\delta^{18}\text{O}$  offset  $\sim 0.49\text{‰}$ ). This pattern points to higher temperatures and/or lower



**Figure 5.** Pacific salinity distributions. (a) Observed present-day salinity, zonally averaged across the South Pacific (WOA) [Antonov *et al.*, 2010]. Red dots indicate the approximate water depth of sediment cores used in this study. (b) Modeled LGM Southern Ocean surface freshwater flux anomaly (m/yr; positive means freshwater flux into the ocean) relative to preindustrial (annual mean; 100 year average). (c) Modeled preindustrial salinity, zonally averaged across the South Pacific (annual mean; 100 year average). (d) As in Figure 5c but for the LGM (salinity adjusted such that global mean salinity is identical to preindustrial). AAIW = Antarctic Intermediate Water, UCDW = Upper Circumpolar Deep Water, and AABW = Antarctic Bottom Water.

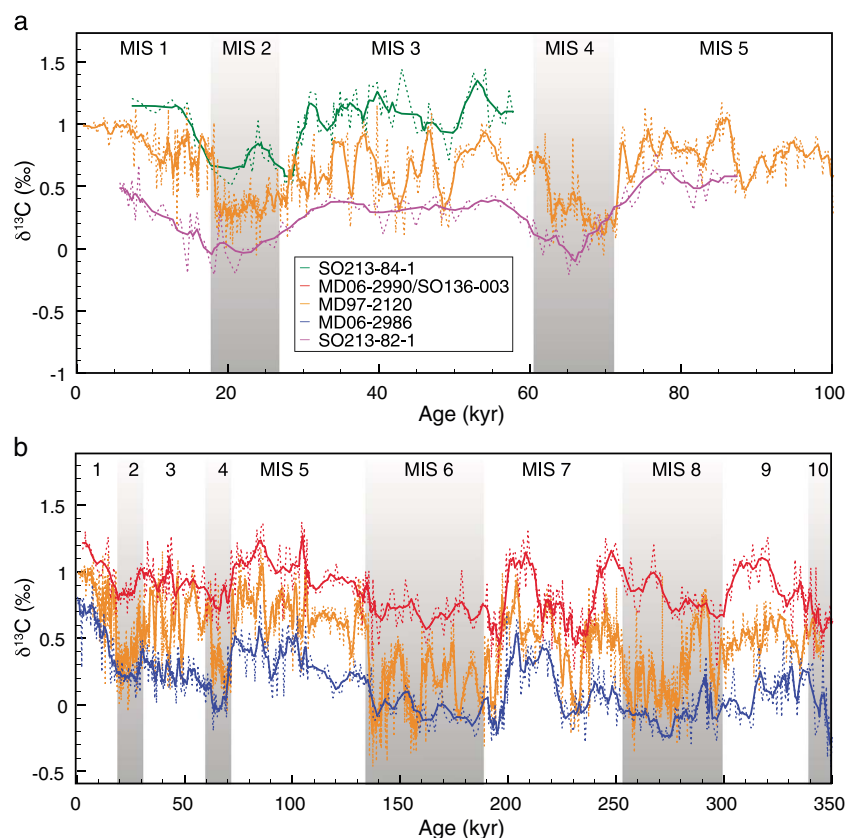
salinity in the intermediate water (Figure 3). Because MD97-2120 shows the highest sedimentation rates ( $\sim 16$  cm/kyr; supplements of Pahnke *et al.* [2003b]) the pronounced amplitudes seen in the isotopic records could be ascribed to the high temporal resolution. Anyway, the proposed alternation of MD97-2120 between AAIW and UCDW that will be discussed below might also explain the high amplitudes of MD97-2120.

### 3.2. Benthic $\delta^{13}\text{C}$

All sediment cores analyzed show similar  $\delta^{13}\text{C}$ -patterns over the whole time interval, oscillating between glacial lows and interglacial highs, with a mean offset of  $\sim 0.7\text{‰}$  between the AAIW and UCDW. The sediment cores bathed by modern AAIW (SO213-84-1 and MD06-2990) and by modern UCDW (SO213-82-1 and MD06-2986) show similar isotopic values of  $1.14\text{‰}$  for the AAIW and  $0.4$  to  $0.6\text{‰}$  for the UCDW (Table S2). Nevertheless, minor differences between Tasman Sea and Bounty Trough  $\delta^{13}\text{C}$  values are evident especially during the last glacial (Figure 4). Throughout the LGM, the isotopic minima in Bounty Trough cores SO213-84-1 (AAIW) and SO213-82-1 (UCDW) are more pronounced than in their Tasman Sea counterparts. Therefore, we would like to mention that the  $\delta^{13}\text{C}$  values of the respective time interval from core SO213-82-1 partly derive from adjusted *U. peregrina* values. Despite similar amplitudes in SO213-84-1 and SO213-82-1 a certain bias, introduced by the recalculation of *U. peregrina* values in SO213-82-1 cannot be completely excluded. In this context, it is noteworthy that the amplitudes for MIS 4 are nearly identical for SO213-82-1 and MD06-2986 with both records exclusively based on *C. wuellerstorfi* in this time interval (Figure 4).

### 3.3. Paleoproductivity

The PP for cores SO213-82-1 and SO213-84-1 amounts to a mean value of  $55 \text{ gC/m}^2/\text{yr}$  and  $\sim 53 \text{ gC/m}^2/\text{yr}$ , respectively (Table S3). Consecutive glacials and interglacials show no prominent rise or drop in the PP (Table S3). Therefore, we detect no meaningful correlation between the changes in PP and  $\delta^{13}\text{C}$ . In accordance to the results of Mackensen *et al.* [2001], we conclude that the  $\delta^{13}\text{C}$  results measured on the epibenthic foraminifer species *C. wuellerstorfi* were not affected by the Phytodetritus Effect [Mackensen *et al.*, 1993].



**Figure 6.** Comparison benthic carbon isotope records (*C. wuellerstorfi* equivalent) for the last (a) 100 kyr (Bounty Trough) and (b) 350 kyr (Tasman Sea) to the Bounty Trough record MD97-2120 [Pahnke and Zahn, 2005]. Bold lines (five-point running average); stippled lines (raw data).

### 3.4. Modeling Study

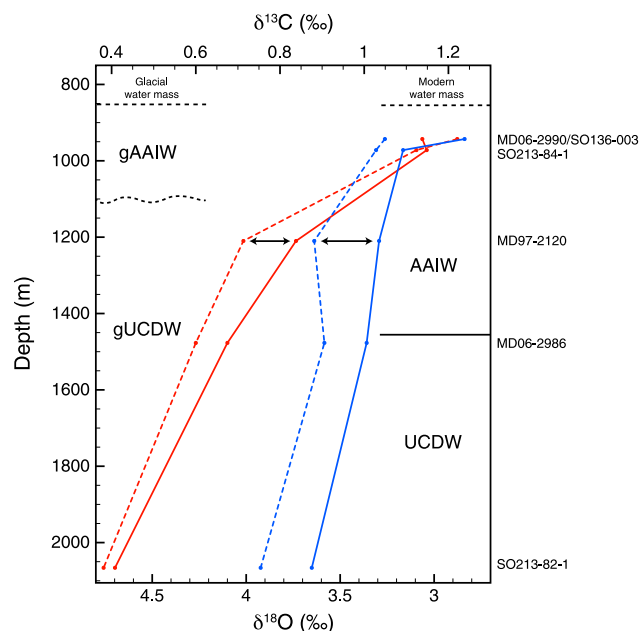
The overall distribution of South Pacific water masses with the characteristic low-salinity tongue of AAIW is clearly expressed in the preindustrial control simulation with the CCSM3 model (Figures 5a and 5c). Compared to observations, however, AAIW forms too far north which is likely related to simulated SWW that are biased toward the north [Varma *et al.*, 2011], a common shortcoming in most coarse-resolution climate models [e.g., Rojas *et al.*, 2009]. Moreover, the modeled AAIW is too shallow and too salty, despite a surface low-salinity bias south of  $\sim 40^{\circ}\text{S}$  (Figures 5a and 5c). These model-data mismatches hamper direct geographical comparisons with proxy records from a specific location and imply that changes in the South Pacific hydrography are likely simulated somewhat too far north. Nevertheless, since the model captures the large-scale water masses relevant for this study, the model results are helpful in explaining glacial-interglacial changes of water mass characteristics and water mass distribution. In particular, enhanced surface freshwater input near the AAIW formation regions from melting sea ice in the LGM simulation (Figure 5b) leads to further freshening of the glacial AAIW ( $<33.5$  psu) which spreads toward the north at a much shallower depth compared to the modern (Figure 5d).

## 4. Discussion

The most obvious result of our study is the constant offset of AAIW to UCDW  $\delta^{13}\text{C}$  over the last 350 kyr, indicating no significant changes in water mass geometry. However, this interpretation is revealed as spurious by including another record bathed in modern AAIW-depth (MD97-2120; 1210 m) [Pahnke and Zahn, 2005], located between the other records used in this study, right at the boundary from AAIW to UCDW (Figure 2).

The pattern shown in Figure 2 locates the sediment cores MD06-2990/SO136-003 (943/958 m) and SO213-84-1 (972 m) close to the core of modern AAIW, today at about 700 m [Heath, 1985]. The deep water cores MD06-2986 (1477 m) and SO213-82-1 (2066 m) are located in UCDW. Despite the proximity of MD06-2986 to the interface of AAIW and UCDW (Figure 7), the very close correlation of  $\delta^{13}\text{C}_{\text{CW}}$  (Figure 4) with the





**Figure 7.** Comparison of averaged Holocene (solid lines) and LGM (dashed lines) benthic  $\delta^{13}\text{C}$  (red) and  $\delta^{18}\text{O}$  (blue) depth profiles. The glacial  $\delta^{13}\text{C}$  values were corrected for the global isotopic shift by adding  $0.38\text{‰}$  [Peterson et al., 2014]. Glacial  $\delta^{18}\text{O}$  values were adjusted according to Waelbroeck et al. [2002] by subtracting  $1.1\text{‰}$ . Black arrows indicate the pronounced isotopic shift in MD97-2120 caused by the shift from AAIW to UCDW. Glacial water mass distribution (gAAIW and gUCDW) as proposed in chapter 4; modern distribution after Carter and McCave [1997], Hayward et al. [2002], Heath [1985], and Sloyan et al. [2010]. Sediment cores (modern water depths) are indicated on the right axis.

glacial  $\delta^{13}\text{C}$  of core MD97-2120 indicates an upward displacement of the AAIW-UCDW interface during glacial maxima. As it is shown in Table S2, the offset of MD97-2120 to MD06-2990/SO136-003 (943/958 m; AAIW) and MD06-2986 (1477 m; UCDW) is almost equal during interglacials, slightly leaning to the well-ventilated AAIW. However, during glacials the  $\Delta\delta^{13}\text{C}_{2120\text{-UCDW}}$  decreases to only  $0.18\text{‰}$  while  $\Delta\delta^{13}\text{C}_{\text{AAIW-2120}}$  increases to  $0.54\text{‰}$  (Table S2 and Figure 6).

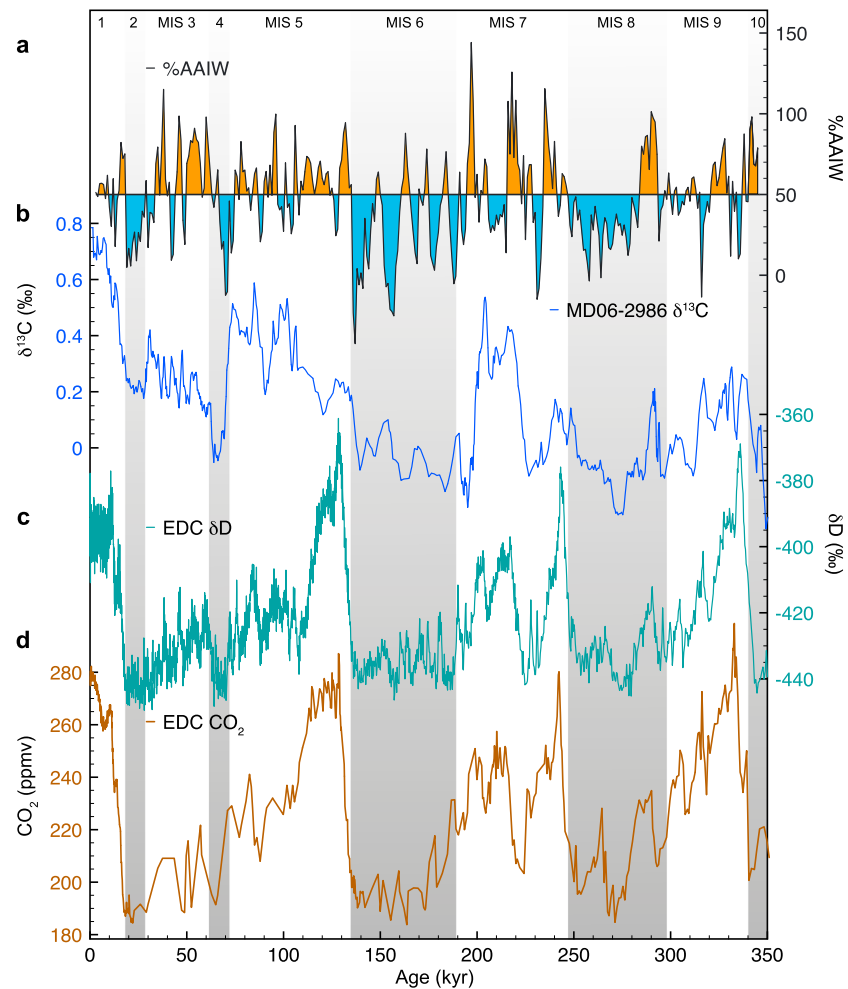
Throughout the Holocene, the  $\delta^{13}\text{C}$  values of MD97-2120 resemble those of SO213-84-1, yielding average values of  $0.83\text{‰}$  and  $1.14\text{‰}$ , respectively (Figure 6). On the other hand, SO213-82-1 shows significantly lower values of  $0.4\text{‰}$ . This pattern reflects the modern water mass distribution (Figure 7), locating MD97-2120 and SO213-84-1 in AAIW and SO213-82-1 in UCDW (Figure 2).

During the Last Glacial Maximum  $\delta^{13}\text{C}$  of MD97-2120 approaches the values of SO213-82-1 ( $0.33\text{‰}$  and  $0\text{‰}$ , respectively). Even though the values of SO213-84-1 also decline, they remain at an average of  $0.74\text{‰}$  and thus considerably higher than the deeper cores. The deep water to intermediate water difference,  $\Delta\delta^{13}\text{C}_{84-82}$  ( $0.74\text{‰}$ ) remains similar to the Holocene offset of  $0.74\text{‰}$ . Therefore, on a glacial/interglacial timescale, MD97-2120 appears to alternate between the water masses assigned to the sediment cores above and below, approaching the water mass interpreted as UCDW in glacial times. This pattern is particularly revealed in Figure 7 (black arrows), where the Glacial-to-Holocene offset in both,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of MD97-2120 is the largest from all sediment cores.

The pattern, with MD97-2120  $\delta^{13}\text{C}$  moving toward UCDW values during glacial maxima and toward AAIW during warmer periods, is repeated throughout the whole time interval analyzed (Table S2). We compared MD97-2120 to MD06-2990/SO136-003 and MD06-2986 on longer timescales, as both SO213 cores span only the last glacial to interglacial cycle (Figure 6). During the warmer stages 3, 5, 7, and 9, the average  $\delta^{13}\text{C}$  values of the shallowest core MD06-2990/SO136-003 (interpreted as AAIW) are as high as  $0.94\text{‰}$ , while MD97-2120

deeper core SO213-82-1 illustrates that MD06-2986 remained in UCDW throughout the last 100 kyr (Figure 4). Therefore, we infer that this setup was maintained over the whole record of 350 kyr. This leaves MD97-2120 [Pahnke and Zahn, 2005] that also lies close to the boundary of AAIW and UCDW, in a crucial position for the investigation of the vertical AAIW extent through time.

During the LGM the  $\delta^{13}\text{C}_{\text{Cib}}$  of AAIW (SO213-84-1 and MD06-2990/SO136-003) and UCDW (SO213-82-1 and MD06-2986) were lower by  $0.34\text{‰}$  and  $0.42\text{‰}$ , respectively, than during the Holocene (Table S2). Thus, this difference fits to the mean whole-ocean  $\delta^{13}\text{C}$  shift of  $0.38\pm 0.08\text{‰}$  [Peterson et al., 2014] and is clearly lower than the AAIW difference found by Bostock et al. [2010] of  $0.8\text{‰}$ . Taking all cycles over the past 350 kyr into account, the isotopic offset between glacials and interglacials for MD06-2990/SO136-003 and MD06-2986 is  $0.19\text{‰}$  and  $0.27\text{‰}$ , respectively. However, the LGM/Holocene offset of MD97-2120 is  $0.53\text{‰}$  and the 350 kyr average offset (MIS1–MIS9) is  $0.41\text{‰}$ . Therefore, we argue that the pronounced depletion in



**Figure 8.** AAIW variability of the southwest Pacific compared to Antarctic ice core records over the past 350,000 years. (a) %AAIW (black) as an indicator for the presence/absence of AAIW in MD97-2120. Orange peaks indicate the presence of AAIW and blue peaks the presence of UCDW. Values higher than 100% and lower than 0% might derive from the comparison of Tasman Sea AAIW to SO-AAIW. (b) Five-point running average benthic (*C. wuellerstorfi*)  $\delta^{13}\text{C}$  record of Tasman Sea core MD06-2986 (blue). (c) EPICA dome C  $\delta\text{D}$ -curve on the AICC2012 timescale (teal) [Bazin *et al.*, 2013; Jouzel *et al.*, 2007; Veres *et al.*, 2013]. (d) Composite  $\text{CO}_2$  curve for the last 350 kyr (brown; 0–22 kyr: EPICA Dome C, [Monnin *et al.*, 2001] and 22–350 kyr: Vostok, [Pépin *et al.*, 2001; Petit *et al.*, 1999; Raynaud *et al.*, 2005]). Grey shadings as shown in Figure 3.

and MD06-2986 display lower averages with 0.65‰ and 0.3‰, respectively. The isotopic offset between MD06-2990/SO136-003 and MD97-2120 ( $\Delta\delta^{13}\text{C}_{2990-2120}$ ) increases during glacial (MIS 6 and MIS 8) from interglacial values of 0.29‰ to a  $\Delta\delta^{13}\text{C}_{2990-2120}$  of 0.54‰ (Figure 8b).

The comparison of sediment cores above and below MD97-2120 suggests an upward displacement of the AAIW-UCDW interface, locating MD97-2120 in poorer ventilated UCDW during the LGM, MIS 4, MIS 6, and MIS 8. These findings are supported by the analysis of the CDW oxygen minimum, which was found at substantially shallower water depths throughout the LGM [Hayward *et al.*, 2004]. Today older and  $\text{CO}_2$  enriched deep waters, like UCDW, are, in general, more corrosive than intermediate waters. Therefore, the findings of Pahnke *et al.* [2003a] who observed increased carbonate dissolution in MD97-2120 throughout cold periods furthermore argues for the presence of corrosive UCDW during glacial periods.

Less pronounced than the AAIW to UCDW shift displayed in the  $\delta^{13}\text{C}$  record of MD97-2120, the  $\delta^{18}\text{O}$  record shows a similar shift from low-salinity, higher-temperature AAIW during warmer climatic periods to higher saline and/or lower temperature UCDW during glacial maxima like the LGM or MIS 4 (Figure 3).

The similarity of benthic  $\delta^{13}\text{C}$  patterns in our cores over the last three glacial-interglacial cycles suggests that source water preformed nutrient changes of AAIW or changes in temperature-dependent fractionation during air-sea gas exchange in the convection region [Broecker and Maier-Reimer, 1992] are negligible.

#### 4.1. Proposed Mechanisms

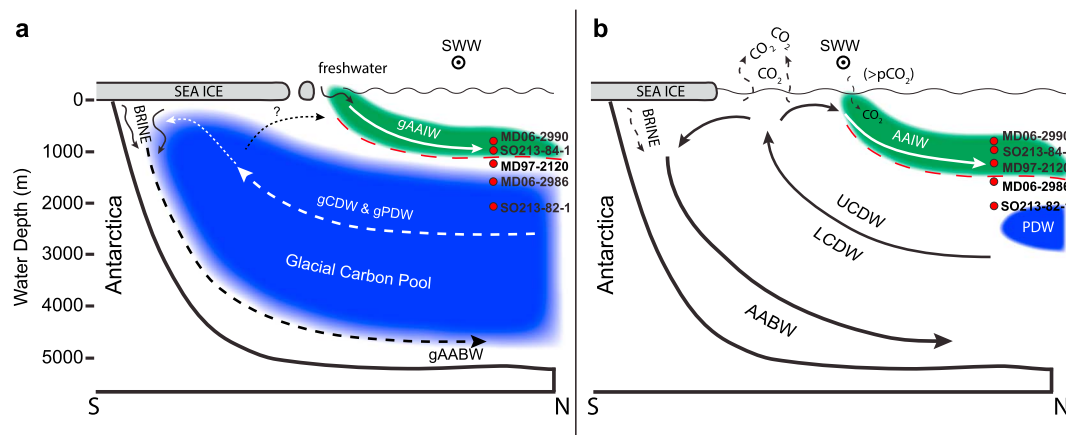
During glacial stages, the boundary, separating high-nutrient (low  $\delta^{13}\text{C}$ ) and  $\text{CO}_2$  rich waters from a better ventilated and low-nutrient water mass rises from  $\sim 2000$  m (interglacials and interstadials) to a depth shallower than 1200 m. This shift could be attributed to several factors: A northward displacement of the AAIW source region, end-member  $\delta^{13}\text{C}$  depletion, increased stratification, decreased biological productivity, increased UCDW upwelling, a reduction in the formation of SO AAIW as proposed by Bostock *et al.* [2004] and Pahnke and Zahn [2005], Carbon Isotope Minimum Events (CIMEs) or reduced AAIW subduction due to increased buoyancy.

During the LGM, the winter sea ice surrounding Antarctica advanced to about the position of the modern Polar Front (PF) [Gersonde *et al.*, 2005]. This advance was accompanied by a northward displacement of Antarctic cold waters, where the strongest cooling occurred within the modern Subantarctic Zone (SAZ) [Gersonde *et al.*, 2005]. According to some authors [e.g., Gersonde *et al.*, 2003; Kohfeld *et al.*, 2013; Sikes *et al.*, 2009], the major oceanic fronts as well advanced toward the north, expanding the surface area of the Southern Ocean. As AAIW is closely associated with Subantarctic Mode Water (SAMW) [Bostock *et al.*, 2004] and SAMW in turn is coupled to the SAF [Hanawa and Talley, 2001], the upward displacement of the AAIW-UCDW interface could be assigned to a northward displacement of the SAF during the LGM. This process would cause SAMW/AAIW to be subducted further to the north (in relation to warmer intervals) extending only to shallower depths at the core locations analyzed in this study. However, Hayward *et al.* [2008] showed that, in the region off New Zealand, neither the SAF nor the Subtropical Front shifted during glacial/interglacial cycles, due to topographic constraints by the Campbell Plateau and the Chatham Rise, respectively (Figure 1). Therefore, we assume a northward shift of the formation region of SO AAIW south of New Zealand [Bostock *et al.*, 2013a] as an unlikely process to explain the upward displacement of UCDW.

A decline of air-sea exchange during glacials due to the northward expansion of sea ice [Gersonde *et al.*, 2005] and/or an equatorward shift in SWW [e.g., Mohtadi and Hebbeln, 2004; Stuut and Lamy, 2004] could have depleted the  $\delta^{13}\text{C}$  due to reduced thermodynamic fractionation in the source region of AAIW [Mackensen, 2012]. However, as our intermediate water records show a similar glacial drop in  $\delta^{13}\text{C}$  as the UCDW records, we propose that this process did not play the dominant role in driving the  $\delta^{13}\text{C}$  pattern in MD97-2120. Increased upper ocean stratification has the potential to lower the  $\delta^{13}\text{C}$  level of a water mass by its separation from high  $\delta^{13}\text{C}$  surface waters. Radiocarbon analyses on cores south of the Chatham Rise indeed constrain a pronounced stratification of the glacial southwest Pacific [Sikes *et al.*, 2000], but place the cline, which separates poorly ventilated waters from overlying waters, below the AAIW at a depth of  $>2000$  m. Therefore, a stratified upper ocean cannot explain the low glacial  $\delta^{13}\text{C}$ . However, mixing with  $\delta^{13}\text{C}$ -depleted waters below the cline cannot be excluded.

The preferential uptake of isotopically lighter  $^{12}\text{C}$  through biological productivity based on photosynthesis [Farquhar *et al.*, 1989] enriches the  $\delta^{13}\text{C}_{\text{DIC}}$  (dissolved inorganic carbon) in a surface water mass. A decrease in biological export production [Francois *et al.*, 1997] in the formation area of AAIW would therefore decrease the  $\delta^{13}\text{C}_{\text{DIC}}$  in source waters. Although this process cannot be completely excluded, we argue it to be unlikely as Hayward *et al.* [2004] report increased biological productivity in the SAZ off New Zealand. The Phytodetritus Effect [Mackensen *et al.*, 2000] on the other hand has the potential to decrease the  $\delta^{13}\text{C}$  in epibenthic foraminifera. However, as we mentioned in the results, we assume that our sediment cores were not affected by a pronounced input of organic carbon.

Pahnke and Zahn [2005] already discussed the process of increased UCDW upwelling as a possible explanation for the very low glacial  $\delta^{13}\text{C}$  values. This process, being in agreement with the  $\delta^{13}\text{C}$  data [Pahnke and Zahn, 2005; this study], could in general explain the isotopic pattern observed in MD97-2120. However, several studies point to decreased glacial upwelling [Boyle and Keigwin, 1982; Sigman and Boyle, 2000] and ventilation [Sikes *et al.*, 2000; Skinner *et al.*, 2010]. Even though increased upwelling cannot be completely ruled out, we consider this scenario as relatively unlikely.



**Figure 9.** Conceptual schemes of SW Pacific water mass structures. (a) Glacial pattern: Associated with advancing winter sea ice, the Southern Westerly Winds (SWW; dotted circle) shift toward the north, away from the formation region of glacial (g) AAIW (green shaded area). Freshwater input from the close sea ice edge enhances gAAIW buoyancy, locating it above the depth of reference core MD97-2120. The blue-shaded area indicates the old [e.g., Sikes *et al.*, 2000] glacial deep-water carbon pool, rich in  $\text{CO}_2$  and nutrients (low  $\delta^{13}\text{C}$ ). During glacial maxima, the AAIW/UCDW interface (red dashed line) shifts above 1200 m, bathing the reference core location of MD97-2120 in low  $\delta^{13}\text{C}$  gUCDW. Dashed arrows indicate a more sluggish deep-water circulation than during interglacial times. Red dots show the modern water depth of sediment cores analyzed in this study. (b) Interglacial pattern: During the warmer stages like the Holocene, the sea ice-derived meltwater input in AAIW declines, while the SWW shift toward a poleward position. Increased AAIW salinity favors a deepening of the AAIW-UCDW interface. Retreating sea ice enables air-sea gas exchange of upwelled CDW, releasing stored  $\text{CO}_2$  toward the atmosphere [e.g., Marchitto *et al.*, 2007; Rose *et al.*, 2010]. During times of high atmospheric partial pressure of  $\text{CO}_2$  ( $>p\text{CO}_2$ ) like today (due to anthropogenic forcing),  $\text{CO}_2$  is being entrained into the ocean interior via AAIW. Thus, today the Southern Ocean acts as a  $\text{CO}_2$  sink, while in preindustrial times (and other interglacials), the SO released upwelled  $\text{CO}_2$  to the atmosphere [e.g., Gruber *et al.*, 2009]. Thick, continuous arrows indicate enhanced ventilation, water mass circulation, and exchange compared to glacial maxima. The old Pacific Deep Water (PDW) carbon pool diminishes and retreats toward its modern dimension [see Key *et al.*, 2004].

Noteworthy features of several intermediate and mode water records at the onset of glacial terminations are pronounced CIMEs [Curry and Crowley, 1987; Ninnemann and Charles, 1997; Spero and Lea, 2002; Ziegler *et al.*, 2013]. A CIME is caused by the reallocation of old (low  $\delta^{13}\text{C}$ ) and  $\text{CO}_2$ -rich waters from the deep Southern Ocean toward the surface by a breakdown in water mass stratification [Spero and Lea, 2002; Ziegler *et al.*, 2013]. The incorporation of these old deep waters into the upper water levels ultimately causes the observed CIMEs [Spero and Lea, 2002]. As Spero and Lea [2002] point out, the deep waters should display an uninterrupted increase in  $\delta^{13}\text{C}$  throughout a CIME. However, as the deep water  $\delta^{13}\text{C}$  in MD06-2986 clearly equals the trend of  $\delta^{13}\text{C}$  in MD97-2120, we argue that the low  $\delta^{13}\text{C}$  values in MD97-2120 do not display the reallocation of old carbon via upwelling during a CIME, but that the very same water mass (UCDW) influenced both sediment cores. Additionally, the fact that CIMEs are relatively short lived [Spero and Lea, 2002] argues against this scenario as the driver for the low  $\delta^{13}\text{C}$  intervals in MD97-2120.

Although the northern Tasman Sea record FR1/97-GC12 (990 m;  $23^\circ 34' \text{S}$   $153^\circ 46' \text{E}$ ) is located close to the core depth of modern AAIW [Bostock *et al.*, 2004], its LGM  $\delta^{13}\text{C}$  values are as low as the  $\delta^{13}\text{C}$  of UCDW records MD06-2986 (1477 m) and SO213-82-1 (2066 m). This implies that in the Tasman Sea as well, glacial AAIW (gAAIW) did not reach as deep as during the Holocene. We conclude that despite findings of increased glacial AAIW formation [Herguera *et al.*, 2010; Martínez-Méndez *et al.*, 2013; Meissner *et al.*, 2005], southern sourced AAIW in the southwest Pacific may not always have reached the core depth of FR1/97-GC12 during the LGM. As Ribbe [2001] suggested, the production of AAIW is closely coupled to the wind stress applied on subantarctic surface waters. He showed that the volume of transported AAIW is in direct proportion to the forcing of southern hemispheric wind stresses. During glacial peak times, the northward displacement of SWW [Mohtadi and Hebbeln, 2004; Moreno *et al.*, 1999; Stuut and Lamy, 2004; Toggweiler *et al.*, 2006] in combination with static oceanic fronts [Hayward *et al.*, 2008] led to a reduction of wind stress in the formation area of SW Pacific AAIW. In addition, the advancing winter sea ice edge increased the glacial import of freshwater by melting sea ice into the AAIW [e.g., Saenko and Weaver, 2001] and thereby intensified the SAZ salinity anomaly [Gersonde *et al.*, 2003; Jenkins, 1999; Pahnke and Zahn, 2005], ultimately hampering the

subduction of AAIW (Figure 9). Furthermore, highly saline bottom waters, stabilized by brine rejection [Adkins, 2013] increased the water column density gradient and thus supported the positive buoyancy of fresher AAIW. A salinity-controlled pattern, leading to shallower penetration of glacial AAIW, is also supported by our CCSM3 model runs (Figure 5) that point to an increased density gradient between glacial water masses (Figure S2). In combination, the processes described here might have significantly reduced the downward extension of AAIW within the southwest Pacific. This void, created by the diminishing influence of glacial AAIW was then filled by an upward displacement of underlying UCDW. We visualized the alternation between AAIW and UCDW by calculating the %AAIW at the core depth of MD97-2120, following the approach of Raymo *et al.* [1990] (Figure 8a; supporting information). %AAIW values higher than 50% indicate the presence of AAIW, values lower than 50% the presence of UCDW at the core location of MD97-2120. At the end of each glacial cycle, the low  $\delta^{13}\text{C}$  of MD06-2990/SO136-003/SO213-84-1 and MD97-2120 increase and approach the same absolute values, while simultaneously, UCDW  $\delta^{13}\text{C}$  of SO213-82-1 and MD06-2986 rises just as rapid (Figure 4). Increasing temperatures in the Southern Hemisphere [e.g., Parrenin *et al.*, 2013] reverse the sequence of glacial processes outlined above. Sea ice retreats and therefore reduces the SAZ freshwater anomaly, the SWW shift toward a poleward position, ultimately increasing the subduction, formation and ventilation of deep and intermediate waters [Toggweiler *et al.*, 2006].

The good correlation between atmospheric  $\text{CO}_2$ ,  $\delta\text{D}$ , and UCDW  $\delta^{13}\text{C}$  and %AAIW (Figure 8) suggests a close coupling of increased deep water ventilation, AAIW formation, and global climate driven by Southern Hemisphere climatic events.

Pahnke and Zahn [2005] proposed that a transient buoyancy inertia caused by meltwater export, delayed the ventilation of AAIW, as their sea surface temperatures (SSTs) of sediment core MD97-2120 lead the increasing  $\delta^{13}\text{C}$  trend by 1–3 kyr. However, we argue that the lead/lag of MD97-2120  $\delta^{13}\text{C}/\text{SST}_{\text{Mg/Ca}}$  is not a consequence of delayed ventilation but of a delayed downward expansion of AAIW and decelerated UCDW ventilation. As already proposed, the enhanced import of meltwater likely led to a buoyancy gain of recently formed AAIW. Only upon a reduction of freshwater input would the AAIW be able to advance to depths greater than about 1200 m. Although the AAIW ventilation occurred at the onset of rising temperatures, the UCDW lagged behind, due to the pool of old and  $\text{CO}_2$ -rich water that had to be ventilated as shown by Skinner *et al.* [2010].

We further speculate that changes in the AAIW freshwater budget might cause global reorganizations in the oceanic Thermohaline Circulation (THC). Saenko *et al.* [2003] showed that the end-member freshwater budget of the THC controls the density gradients of AAIW and North Atlantic Deep Water (NADW) and therefore their formation rate. Freshwater input in one hemisphere can significantly alter the AAIW-NADW density gradient, enhancing, or hampering the formation rate of the respective water mass in the opposing hemisphere [Weaver *et al.*, 2003].

Radiocarbon analyses on planktic and benthic foraminifera proved the presence of exceptional old waters within glacial CDW in the southwest Pacific and South Atlantic [Sikes *et al.*, 2000; Skinner *et al.*, 2010]. At the onset of the most recent deglaciation, deep water ventilation improved simultaneously with the increase in AAIW subduction, outlined above. The restart of the Southern Ocean Meridional Overturning Circulation [Sigman *et al.*, 2010] conveyed ancient  $\text{CO}_2$  from the deep ocean toward the surface and ultimately to the atmosphere. During this process of upwelling and the subsequent formation of intermediate waters, the incomplete air-sea gas exchange favored the incorporation of  $^{14}\text{C}$ -depleted old waters in AAIW (MD97-2120) during Heinrich Stadial 1 [Rose *et al.*, 2010]. In this context a radiocarbon-based analysis of MD97-2120 during the last glacial would contribute to the results discussed above, as we expect the  $^{14}\text{C}$  values of MD97-2120 to decrease as well in intervals marked by the presence of weakly ventilated  $\delta^{13}\text{C}$ - and  $^{14}\text{C}$ -depleted UCDW.

## 5. Conclusions

Recent benthic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  records from the Bounty Trough and the Tasman Sea off New Zealand allow new insights into the formation and extent of SW Pacific AAIW over the last 350 kyr. The new proxy data and modeling results presented in this study question the hypothesis that stronger water column



stratification resulted in reduced production of glacial AAIW [Pahnke and Zahn, 2005]. Our results suggest that a northward displacement of the winter sea ice edge [Gersonde et al., 2005] led to a significantly shallower AAIW subduction in the SW Pacific during glacial maxima. Warmer climatic conditions on the other hand favor the enhanced downward extent of AAIW (Figure 9).

Following the synchronous timing of these observations and published SSTs [Pahnke and Zahn, 2005], we conclude that pronounced climate changes in the Southern Hemisphere are the dominating factor, driving changes in AAIW formation, its vertical expansion as well as the ventilation and the associated carbon storage and cycling of CDW.

Vast amounts of anthropogenic CO<sub>2</sub> are transported toward the deep ocean via the AAIW [Downes et al., 2010; Murata et al., 2007, 2010; Sabine et al., 2004], while at the same time stored CO<sub>2</sub> is upwelled within CDW [Gruber et al., 2009] (Figure 9). As model predictions suggest, the current CO<sub>2</sub> sink of the Southern Ocean [Gruber et al., 2009] might evolve into a source due to the poleward shift of SWW and the accompanying increase in CDW upwelling [Le Quéré et al., 2007]. Additional modeling studies [Downes et al., 2010; Manabe and Stouffer, 1993] showed that this process might be reversed on longer timescales, leading to increased ocean stratification and decreased AAIW formation and consequently to a reduction in the uptake of anthropogenic CO<sub>2</sub>. Thus, in order to specify the Southern Ocean's role in the carbon cycle of a changing climate system, improved insight in this highly dynamic system is essential.

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